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CAPABILITY DEVELOPMENT OF ADHESIVE BONDED STUDS

Covering Period
1 December 1962 through 30 October 1963

F. M. Wilson 15 Nov. 1963 66p refs

Final Summary Report

Contract NAS8-5188
RFQ No. 3-82116
Control No. TP 3-84037 (IF)

15 November 1963

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Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

FOREWORD

This report was prepared by Narmco Research & Development, a Division of Telecomputing Corporation, San Diego, California, under Contract No. NAS 8-5188, Control No. TP 3-84037 (IF), entitled "Capability Development of Adhesive Bonded Studs," for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama. The work was administered under the direction of M-P&C-CA, George C. Marshall Space Flight Center, with Mr. William J. McKinney acting as Contracting Officer.

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ABSTRACT

This Final Summary Report outlines the development of the load-carrying capability of adhesive bonded studs. Four resin systems and two flexible liners in two thicknesses were investigated, and the test results of the various combinations of these materials indicated the optimum bonding system. Bonding procedures are outlined and the importance of following these procedures is stressed. This program resulted in a room temperature adhesive system with a load-carrying ability exceeding that of the stud.

AUTHOR

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I. PHASE I

A. INTRODUCTION

The following summary report covers the period 1 December 1962 through 28 February 1963 and briefly describes the work which has been accomplished during Phase I of this program. The work accomplished during the period 1 February 1963 through 28 February 1963 is described in somewhat more detail.

Work was initiated on the subject contract 30 November 1962. An analysis on optimum shape of the stud base plate was completed and is included as Appendix A to this report. Based on this analysis, designs have been completed on the 1/4-in. and 3/8-in. diameter studs. A drawing of this design, RE 5326, is attached. Studs have been manufactured according to this design in the 1/4-in. and 3/8-in. diameters. 5456 anodized aluminum base plates measuring 6 in. x 6 in. x 1/4 in. have been procured.

B. BONDING SYSTEMS

The systems for bonding studs to base plates chosen for investigation during Phase I are as follows:

1. Adhesives

Based on past experience and a brief literature survey, the following adhesive systems have been chosen for investigation during Phase I of the contract task:

a. Narmco 3135/7111
Room temperature curing epoxy-polyamide, two-part system

b. Narmco 7343/7139
Room temperature curing polyurethane elastomer, two-part system

c. Narmco X305
Room temperature curing polyurethane modified epoxy, one-part system

d. Narmco 3170/7133
Room temperature curing Nylon-filled epoxy polyamide, two-part system

2. Flexible Film Shock Absorbers

a. Teflon FEP, Type 544

b. Polyurethane film (Estane, Texin or multrathane)

3. Flexible Film Thicknesses

a. Single 1-mil films: composite glueline thickness 4-7 mils

b. Single 50-mil films: composite GLT 8 - 11 mils

c. No flex film: GLT adhesive only 3-6 mils

Tooling for performing the various tests, as outlined in all phases of the program, were incorporated into one tool. This tool consists of an open-top box fabricated from 1-in. aluminum plate measuring 7-in. x 7-in. x 5-in. with hold-down clamps for the 6-in. x 6-in. test plates. One side can be removed for use as a shear test fixture and the other sides and bottom have been predrilled to mount on the shock and vibration machines. The relatively heavy aluminum plate was selected as the tooling material so that the possibility of generating a resonant frequency in the box during the vibration tests would be minimized.

C. TESTING

The initial tests were conducted on X-305 with 5-mil Estane, using the loading nut as shown in Figure 1. This nut indexed to the end of the stud so that the load was applied 1 in. from the bonded face of the stud. However, when the studs failed at 967 lb and 920 lb (see Table 1), it was realized that the load had to be transferred to the shoulder of the stud. This was accomplished by modifying the loading nut so that it indexed to the 0.600-in. diameter shoulder of the stud and still retained the loading point at 1 in. from the bonded face of the stud. The revised loading nut, as shown in Figure 2, was used in all the remaining tests. All tests were conducted in static shear. The plate with its bonded stud was loaded into the test fixture so that the plate was supported in a vertical position. The test fixture was then placed in the 60,000-lb Tinius-Olsen hydraulic test machine.

Centered over the loading nut, which had been seated on the stud shoulder, a load was applied at a head travel rate of approximately 0.050 in./min. The test setup as described is shown in Figure 3.

D. TEST RESULTS

The results of each individual test and averages are given in Tables 1, 2, 3, 4, and 5. As will be noted, the X-305 Estane system had the highest average strengths and was the only system that developed higher strengths than that of the 3/8-in. diameter studs.

Five additional specimens were fabricated using the X-305 1-mil Estane system for the purpose of obtaining a stress-strain curve as the specimens were tested. The ultimate load deflection values for stress-strain curves are given in Table 6, and the curves are shown in Figures 4 through 8.

The average failing load for these additional five specimens was 1458 lb, with one outstanding specimen at 1930 lb. This indicates that operator technique has much to do with the efficiency of the stud-to-plate bond, since all other factors were identical with the first tests run. Such things as operator skill in eliminating all entrapped air and controlling glueline thickness probably are controlling factors in the strengths that can be obtained. It is anticipated that as the fabrication techniques are perfected and standardized, the average strength of the bonded studs will approach the highest obtained to date.

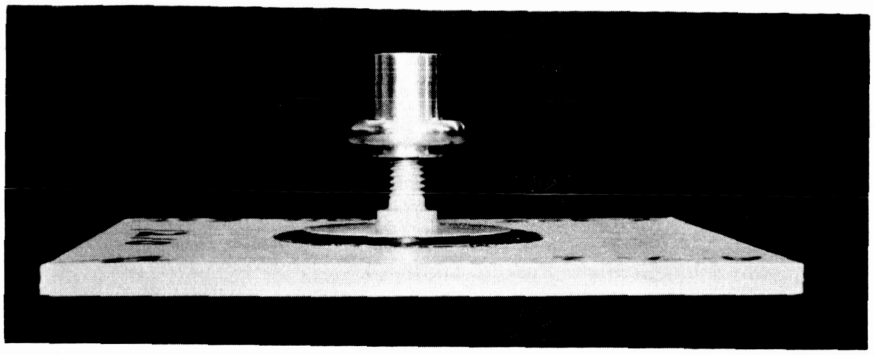


Figure 1. Original Loading Nut

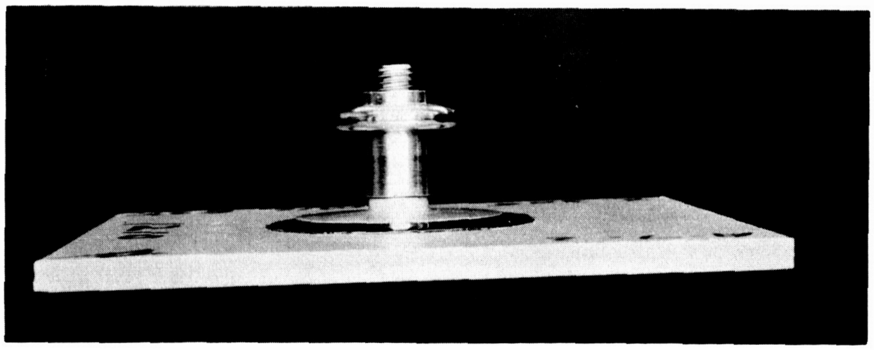


Figure 2. Revised Loading Nut

TABLE 1

TEST RESULTS X-305 ADHESIVE

	Specimen No.	Adhesive	Bondline	Load, lb	Type of Failure
	A-1-1	X-305	1-mil Estane	1790	Broke stud
	A-1-2			992	Broke stud
	A-1-3			740	Broke stud
	A-2-1		5-mil Estane	1460	Cohesive
	A-2-2			967	Broke stud*
	A-2-3			920	Broke stud*
	A-3-1		5-mil Teflon	510	Cohesive
	A-3-2			640	Cohesive
	A-3-3			700	Adhesive failure
	A-4-1		1-mil Teflon	550	Adhesive
	A-4-2			570	Adhesive
	A-4-3			385	Adhesive failure
	A-5-1		0.004 wire shim	822	Cohesive
	A-5-2			850	Cohesive
	A-5-3			795	Cohesion failure
	A-6-1		P.C. wire shim	1105	Cohesive
	A-6-2			1150	Cohesive
	A-6-3			880	Cohesion failure
	A-7-1		1-mil Estane	1170	Cohesion
POSTCURED 200°F - 1 HOUR	A-7-2			1210	
	A-7-3			910	
	A-8-1		5-mil Estane	1600	
	A-8-2			900	
	A-8-3			900	

* Failed at 967 lb and 920 lb

X-305 SYSTEM AVERAGES

1-mil Estane	Av. (3)	1174
5-mil Estane	Av. (3)	1157
1-mil Estane	Postcured Av. (3)	1097
5-mil Estane	Postcured Av. (3)	1133
X-305 Estane	Av. (12)	1140
1-mil Teflon	Av. (3)	502
5-mil Teflon	Av. (3)	617
X-305 Teflon	Av. (6)	560
No Flex Line	Av. (3)	822
No Flex Line	Postcured Av. (3)	1045
	Av. (6)	934
X-305	Av. (24)	943

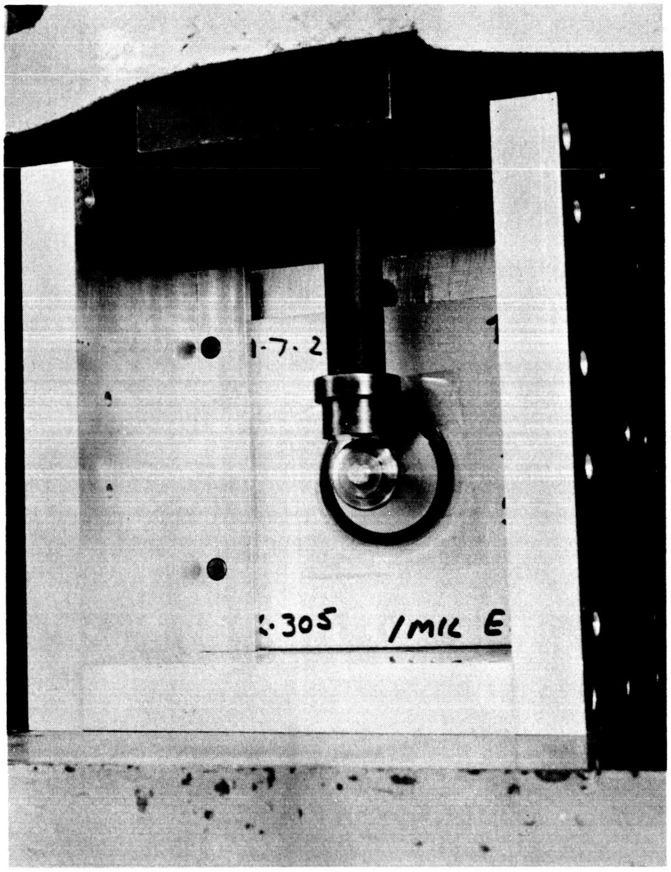


Figure 3. Test Setup in 60,000-lb Tinius-Olsen

TABLE 2

TEST RESULTS 3135/7111 ADHESIVE

Specimen No.	Adhesive	Bondline	Load, lb	Type of Failure
B-1-1	3135	1-mil Estane	811	Adhesive failure
B-1-2			570	
B-1-3			270	
B-2-1		5-mil Estane	881	Cohesive - Bent stud
B-2-2			800	Adhesive
B-2-3			1750	Adhesive
B-3-1		5-mil Teflon	578	Cohesive
B-3-2			545	
B-3-3			745	
B-4-1		1-mil Teflon	505	
B-4-2			446	
B-4-3			420	
B-5-1		Wire shim 0.004	620	
B-5-2			834	
B-5-3			384	

3135 System Averages

1-mil Estane	Av. (3)	550
5-mil Estane	Av. (3)	1144
3135 Estane	Av. (6)	847
1-mil Teflon	Av. (3)	457
5-mil Teflon	Av. (3)	623
3135 Estane	Av. (6)	540
No Flux Liner	Av. (3)	613
3135	Av. (15)	677

TABLE 3

TEST RESULTS 7343/7131 ADHESIVE

Specimen No.	Adhesive	Bondline	Load, lb	Type of Failure
C-1-1	7343	5-mil Estane	620	Adhesive
C-1-2			605	
C-1-3			830	
C-2-1		1-mil Estane	741	
C-2-2			812	
C-2-3			714	
C-3-1		1-mil Teflon	846	
C-3-2			243	
C-3-3			868	
C-4-1		5-mil Teflon	713	
C-4-2			735	
C-4-3			915	
C-5-1		Wire shim 0.004	908	
C-5-2			849	
C-5-3			794	

7343 System

1-mil Estane	Av. (3)	756
5-mil Estane	Av. (3)	685
7343 Estane	Av. (6)	721
1-mil Teflon	Av. (3)	819
5-mil Teflon	Av. (3)	788
7343 Teflon	Av. (6)	804
No Liner	Av. (3)	850
7343	Av. Results (15)	780

TABLE 4

TEST RESULTS 3170/7133 ADHESIVE

Specimen No.	Adhesive	Bondline	Load, lb	Type of Failure
D-1-1	7133	1-mil Estane	1151	Cohesive
D-1-2			1124	
D-1-3			1154	
D-2-1		5-mil Estane	1190	
D-2-2			809	
D-2-3			952	
D-3-1		5-mil Teflon	626	
D-3-2			662	
D-3-3			739	
D-4-1		1-mil Teflon	579	
D-4-2			502	
D-4-3			467	
D-5-1		Wire shim 0.004	640	
D-5-2			673	
D-5-3			792	

7133 System

1-mil Estane	Av. (3)	1143
5-mil Estane	Av. (3)	984
7133 Estane	Av. (6)	1064
1-mil Teflon	Av. (3)	516
5-mil Teflon	Av. (3)	676
7133 Teflon	Av. (6)	596
No Flex Liner	Av. (3)	702
7133	Av. (15)	804

TABLE 5

FLEXIBLE FILM AVERAGES

1-mil Estane	Av. (15)	944
5-mil Estane	Av. (15)	1021
Estane	Av. (30)	983
1-mil Teflon	Av. (12)	574
5-mil Teflon	Av. (12)	675
Teflon	Av. (24)	625
No Flex Liner	Av. (15)	806
Av. of All Tests	(69)	804

TABLE 6

ULTIMATE LOAD DEFLECTION VALUES
FOR STRESS-STRAIN CURVES

X-305 — 1-MIL ESTANE

Specimen No.	Ultimate Load, lb	Deflection, in.
G-1-1	1540	0.0698
G-1-2	1160	0.0468
G-1-3	1330	0.0676
H-1-1	1930	0.110
H-1-2	Not Tested	Not Tested
H-1-3	1330	0.0535

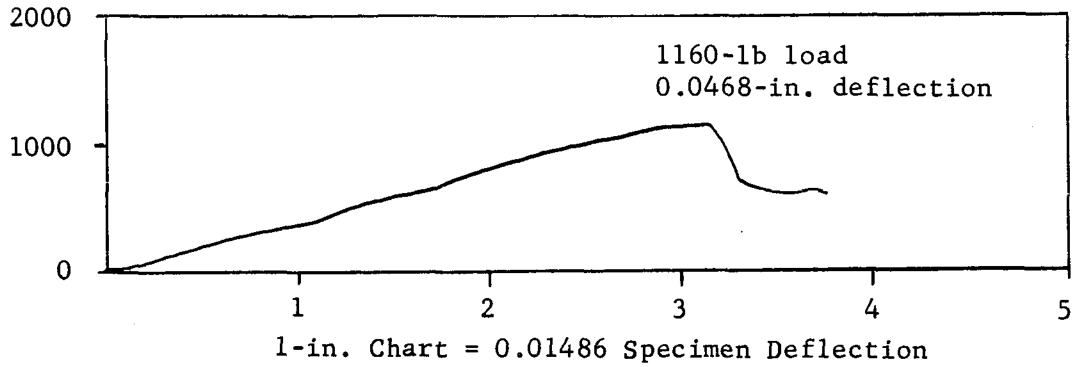


Figure 4. G-1-2 Specimen Load Deflection Curve

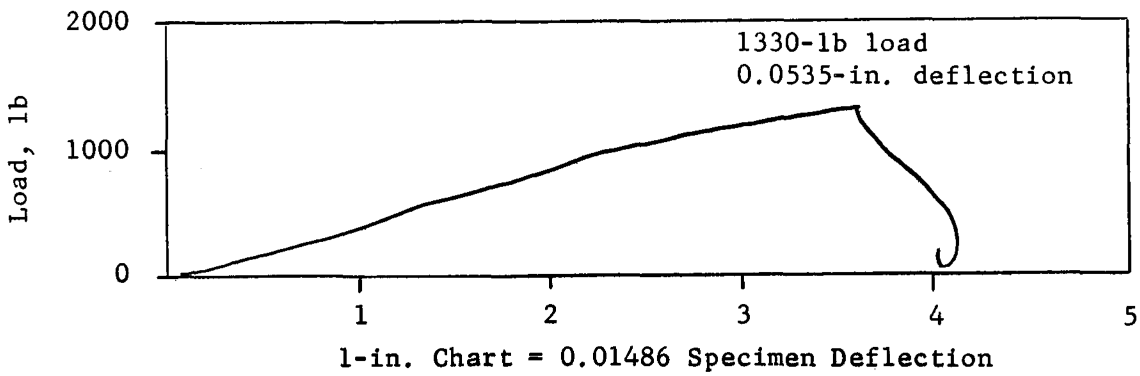


Figure 5. H-1-3 Specimen Load Deflection Curve

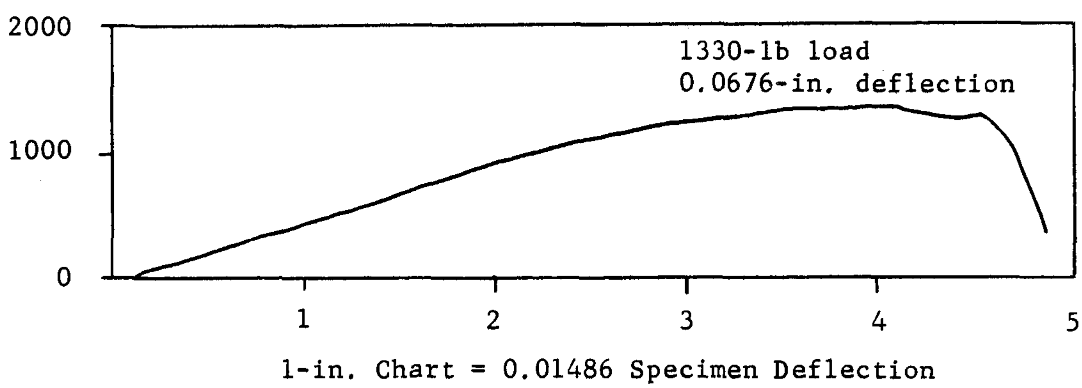


Figure 6. G-1-3 Specimen Load Deflection Curve

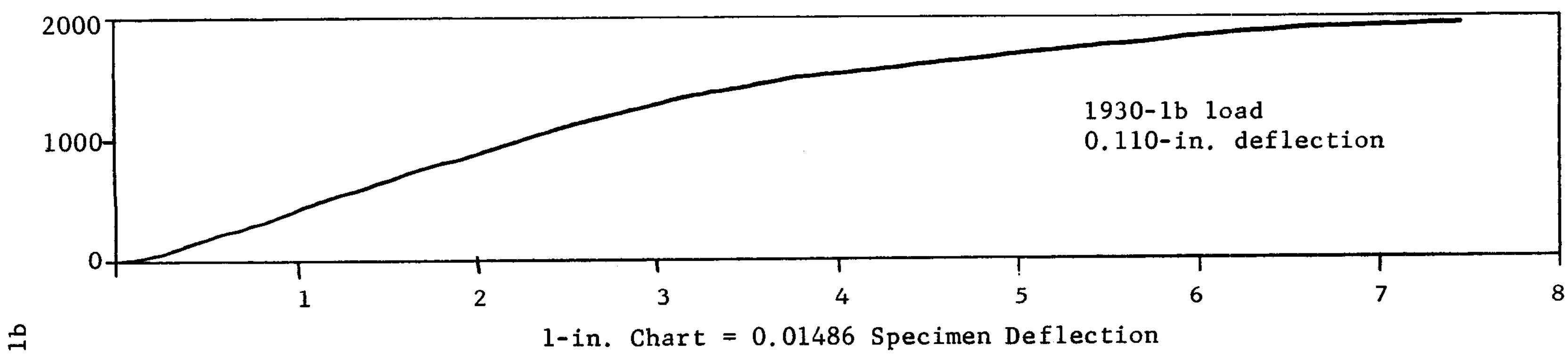


Figure 7. H-1-1 Specimen Load Deflection Curve

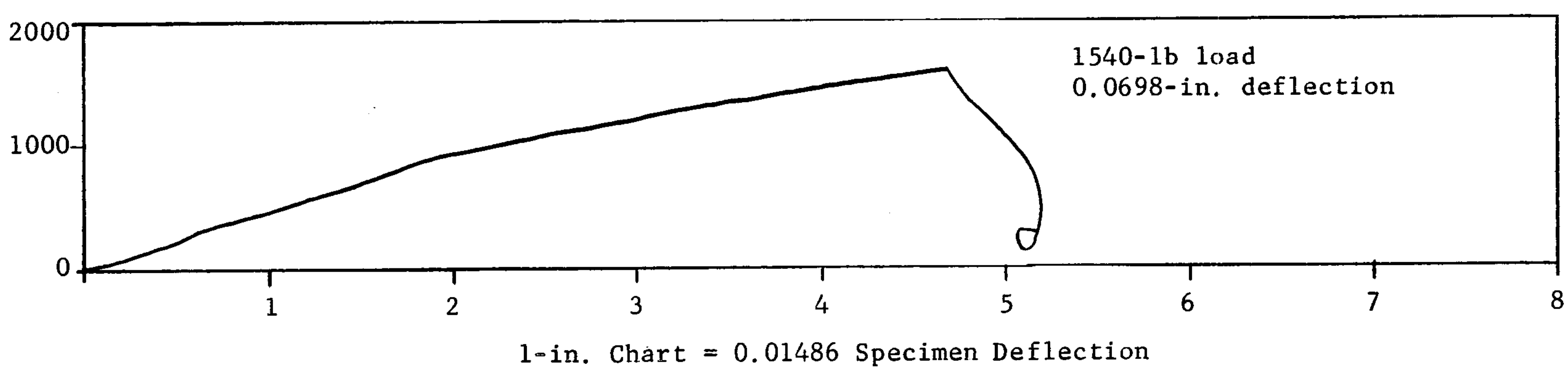


Figure 8. G-1-1 Specimen Load Deflection Curve

E. BONDING PROCEDURE

The studs and plates were degreased, rinsed, and air dried. Care was taken thereafter not to touch the bonding surfaces with the fingers.

By using a mask of Mylar, a 4-mil layer of adhesive was applied to the center of the 5456 aluminum plates. The flexible film was carefully wiped with MEK, air dried, then applied to the adhesive. Care was taken to prevent trapping air under the film. A second 4-mil layer of adhesive was applied to the flexible film and a third layer to the bonding face of the stud. The stud was then applied to the flexible film with a rolling motion to remove all entrapped air. The plates, with the affixed studs, were then placed face up on a curing rack and a 2-lb weight applied to each stud. All adhesive systems then were allowed to cure for 72 hours at room temperature, with the exceptions of the A-6, A-7, and A-8 series in Table 1. These nine studs were postcured at 200°F for 1 hour for the purpose of checking the effects of postcure on this adhesive system.

The average values of the various adhesion systems, using a Teflon flexible film, are in every case lower than the average values obtained when no flexible film was used. It is felt that this fact eliminates a Teflon flexible liner from further consideration. With the exception of the 7343 adhesive system, improvement was shown by the addition of an Estane flexible film. Since the 7343 system displayed the lowest averages when used with Estane and had no really good specimens in any of the combinations, it has been eliminated from further consideration.

The 3135 system displayed the lowest average value of the four systems with only one outstanding specimen. This indicates a good potential adhesive system; however, it probably has processing difficulties. For these reasons, the 3135 adhesive system has been eliminated from further consideration. On the two resin systems remaining (S-305 and 7132), some average improvement is shown by the addition of an Estane flexible film. Although the tests to date show that the 1-mil film is slightly superior to the 5-mil film, it would be reasonable to believe that the 5-mil film would exhibit superior shock and vibration resistance.

II. PHASE II

A. INTRODUCTION

The following summary report covers the period 1 May 1963 through 31 August 1963 and briefly describes the work which has been accomplished during Phase II of this program. The work performed during the period 1 August 1963 through 31 August 1963 is described in more detail.

Two resin systems (X-305 and 3170/7133) and two thicknesses of flexible liner (0.002 in. and 0.005 in.) have been investigated. A series of six tests has been conducted on each of the four bonding systems, using approximately ten specimens each. Results of these tests have been grouped so that the optimum system can be selected.

B. BONDING SYSTEMS

The systems for bonding studs to base plates chosen for investigation during Phase II of the contract task are as follows (the adhesive systems listed are based on results of tests performed during Phase I):

1. Adhesives

   a. Narmco X-305
   Room temperature curing polyurethane modified epoxy, one-part system

   b. Narmco 3170/7133
   Room temperature curing nylon-filled epoxy polyamide, two-part system

2. Flexible Film Shock Absorbers

   a. Estane film (polyurethane) 0.002-in. thick

   b. Estane film 0.005-in. thick

C. TESTING

Testing on adhesive-bonded studs during Phase II of this program was performed on approximately ten specimens of each bonding system for each of the following tests:

1. Static Tensile
2. Shock Shear
3. Shock Tensile
4. Vibration

Tooling for performing these tests was incorporated into one piece of equipment consisting of an open-top box fabricated from 1.0-in. thick aluminum plate measuring 7.0 in. x 7.0 in. x 5.0 in. with hold-down clamps for the 6.0-in. x 6.0-in. test plates. One side can be removed for use as a shear test fixture, and the other sides and bottom have been predrilled to mount on the shock and vibration machines. The relatively heavy aluminum plate was selected as the tooling material so that the possibility of generating a resonant frequency in the box during the vibration tests would be minimized.

1. Static Tension Testing

Results of the static tension tests are shown in Tables 7 through 10. During the testing of the X-305 1-mil Estane system, it was discovered that the tension fixture was flexing under tension and was inducing a partial side (or tearing) load on the specimen. The tests were stopped and remedial action taken. Specimens Nos. 1, 2, and 8 were tested in the reworked fixture. The resulting values indicated that a reduction in ultimate load (approximately 10%) was caused by the side loading.

As can be seen from Tables 7 through 10, the bonding system utilizing X-305 adhesive with 0.001-in. thick Estane developed considerably more strength in static tension than did the other systems tested. When used with 0.005-in. thick Estane, the 3170/7133 adhesive showed a small advantage over the X-305 system. If the three adhesives failures (evidence of improper cleaning procedures) are not considered, the X-305 adhesive is slightly better.

When 0.005-in. Estane is used, the limiting factor for bond strength is the film-adhesive interface, due either to the stresses caused by the effect of Poisson's ratio or to necking down of the flexible film. This necking down is greatly reduced with the use of 0.001-in. flexible film, with a considerable increase in bond strengths.

The average bond strength of the X-305 system with 0.001-in. Estane was 4010 lb, or approximately 80% of the ultimate tensile strength of the 3/8-in. diameter stud.

2. Tensile Shock Tests

All tensile shock tests were conducted using an Avco-type SM 005-1 shock tester with a Tektronic-type 543 oscilloscope and a camera, coupled with an Endevco-type 2215 accelerometer. This setup produced a shock pattern on the oscilloscope that was photographed by the camera. For economical reasons, all shocks on all specimens were not recorded by the camera. The shock machine was calibrated prior to the test run, and driving air pressure was coordinated with the resultant shock. Spot checks were made throughout the test, and a final check was made when the test was completed to assure nonvariation of the calibration. The test fixture was attached to the shock machine so that the specimen plate was suspended with the stud pointing downward. In order to place the stud in tension during the deceleration shock, a 10-lb weight was screwed onto the stud. (Results of the test are shown in Tables 11 through 14.)

Results of the tests on 7133/7130 adhesive with 0.002-in. thick Estane flexible film (Table 11) were somewhat erratic, with only one cohesive failure at 200 g's. The 7133/7130 adhesive with 0.005-in. Estane film was much more consistent, with all failures cohesive at approximately 200 g's.

TABLE 7

STATIC TENSILE TEST

X-305 Adhesive With 0.005-in. Estane Flex Film
On 5456 T6 Bare Aluminum (Not Etched)

Specimen No.	Load, lb	Remarks
1	2950	
2	1650	Adhesive failure
3	2450	
4	2360	
5	2520	
6	2740	
7	2960	
8	1800	Adhesive failure
9	1980	Adhesive failure
10	3020	
	Av. 2443	

NOTE: Loading Rate = 0.050 in./min

TABLE 8

STATIC TENSILE TEST

3170/7133 Adhesive With 0.001-in. Estane Flex Film
On 5456 T6 Bare Aluminum (Etched)

Specimen No.	Load, lb.	Remarks
1	2860	Failures of all specimens were cohesive at film-adhesive interface
2	3000	
3	2620	
4	2450	
5	2780	
6	2320	
7	2550	
8	2470	
9	2560	
10	2270	
	Av. 2588	

NOTE: Loading Rate = 0.050 in./min

TABLE 9

STATIC TENSILE TEST

X-305 Adhesive With 0.001-in. Estane Flex Film
On 5456 T6 Bare Aluminum (Etched)

Specimen No.	Load, lb	Remarks
1*	4840	All failures were cohesive at film-adhesive interface
2*	5230	
3	3850	
4	3890	
5	3900	
6	3550	
7	3460	
8*	4200	
9	3390	
10	3810	
	Av. 4010	

* Reworked fixture

NOTE: Loading Rate = 0.050 in./min

TABLE 10

STATIC TENSILE TEST

3170/7133 Adhesive With 0.001-in. Estane Flex Film
On 5456 T6 Bare Aluminum (Etched)

Specimen No.	Load, lb	Remarks
1	2430	All failures were cohesive at film-adhesive interface. All tests were made in reworked fixture.
2	2470	
3	2470	
4	2720	
5	2420	
6		Not tested
7	2120	
8	2200	
9	2500	
10	2300	
	Av. 2400	

NOTE: Loading Rate = 0.050 in./min

TABLE 11

TENSILE SHOCK TESTS

7133/7130 Adhesive With 0.002-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	130 146	5 1	
2	130 146	5 1	All failures adhesive except No. 9, which was cohesive
3	200	1	
4	146	1	
5	138 146	5 1	
6	138	1	
7	138	1	
8	138	1	
9	138 146 185 200	5 5 5 5	
10	138 146	5 5	

TABLE 12

TENSILE SHOCK TESTS

7133/3170 Adhesive With 0.005-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	75	5	All failures cohesive
	110	5	
	120	5	
	130	5	
	146	5	
	185	5	
	200	5	
2	185	5	
	200	3	
3	200	4	
4	200	5	
	216	4	
5	200	5	
	216	2	
6	200	2	
7	200	5	
	216	1	
8	200	1	
9	200	4	
10	200	5	
	216	3	

TABLE 13

TENSILE SHOCK TEST

X-305 Adhesive With 0.002-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	130	1	All failures adhesive
2	130	2	
3	130	1	
4	100 110 120 130 146 180 200 216 230 250 260	5 5 5 5 5 5 5 5 5 5 2	Specimen No. 4 was subjected to a total of 52 shocks of increasing intensity and failed on the second 260 g shock
5	130	2	
6	100	1	
7	100	1	
8	100	1	
9	100	1	

TABLE 14

TENSILE SHOCK TEST

X-305 Adhesive With 0.005-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	130	2	All failures adhesive
2	130	2	
3	130	4	
4	130	2	
5	130	5	
	146	5	
	185	1	
6	130	1	
7	130	1	
8	130	1	
9	130	1	
10	130	1	Specimen No. 10 was
	146	5	subjected to a total
	185	5	of 29 shocks of in-
	200	5	creasing intensity.
	216	5	Failure occurred on
	230	5	the third 250 g shock
	250	3	

TABLE 14

TENSILE SHOCK TEST

X-305 Adhesive With 0.005-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	130	2	All failures adhesive
2	130	2	
3	130	4	
4	130	2	
5	130	5	
	146	5	
	185	1	
6	130	1	
7	130	1	
8	130	1	
9	130	1	
10	130	1	Specimen No. 10 was subjected to a total of 29 shocks of increasing intensity. Failure occurred on the third 250 g shock
	146	5	
	185	5	
	200	5	
	216	5	
	230	5	
	250	3	

These tests gave strong indications that the cohesive strength of the 7133/3170 adhesive is the limiting factor, and that 200 g's acceleration (when the stud is supporting a 10-lb weight) is all that can be expected.

Test results for the X-305 adhesive with 0.002-in. Estane film were even more erratic. However, all failures were adhesive, and sustained shock loads were as high as 260 g's on one exceptional specimen.

Test results for the X-305 adhesive with 0.005-in. Estane film were also erratic. There is little reason to assume that one film thickness is better than the other in these tests.

It should be noted that the loading on the X-305 adhesive specimens did not reach the cohesive strength of the adhesive, and that all failures must be considered premature. Investigation after the tests revealed that the baths used for etching the specimens were not functioning at full efficiency, which may account for all failures being adhesive.

Five additional specimens were fabricated from the X-305 5-mil system for purposes of rechecking the levels attainable with new etch solution. Results of these tests are shown in Table 15.

A comparison of the results obtained in Table 14 and Table 15 shows a considerable improvement. The best specimen (No. 10) in Table 11 failed after 29 shocks up to 250 g's, whereas the worst specimen (No. 1) in Table 15 failed after 24 shocks up to 260 g's (the failure was initiated in the flange area of the stud). This verifies the assumption that proper metal surface preparations and rigid adherence to the bonding procedures is of primary importance in obtaining adhesive bonds of high load-carrying capabilities.

Figure 9 is a photograph of the three studs with flange area failures (described in Table 15). Figure 10 shows the deformation of the base plate caused by the shock tensile load. An identical plate not previously loaded was put into the Tinius-Olsen Tester and a compressive load applied. A total deformation of 0.150 in. (before springback) at a load of 2500 lb was required before the permanent plate deformation of 0.070 in. (shown in the photograph) resulted. Since any base plate deformation will cause areas of stress concentration, and since this same deformation has been evidenced during static tensile tests, it is expected that 100% stud or flange failures could be expected when bonded to rigid base plates. Conversely, the load-carrying ability of the adhesive-bonded studs could be expected to be materially lowered as the base plate becomes more flexible.

Table 15 reveals that X-305 resin used with 0.005-in. Estane flex film is the outstanding adhesive system and could be considered better in shock shear resistance than the stud itself.

TABLE 15

TENSILE SHOCK TESTS (Rerun)

X-305 Adhesive With 0.005-in. Estane Film

Specimen No.	Load In G's	No. of Shocks	Remarks
1	200	5	
	216	5	
	230	5	
	245	5	
	260	4	Flange failure
2	260	5	
	275	3	Flange failure
3	290	3	Cohesive failure
4	290	2	Cohesive failure
5	290	5	
	305	1	Flange failure

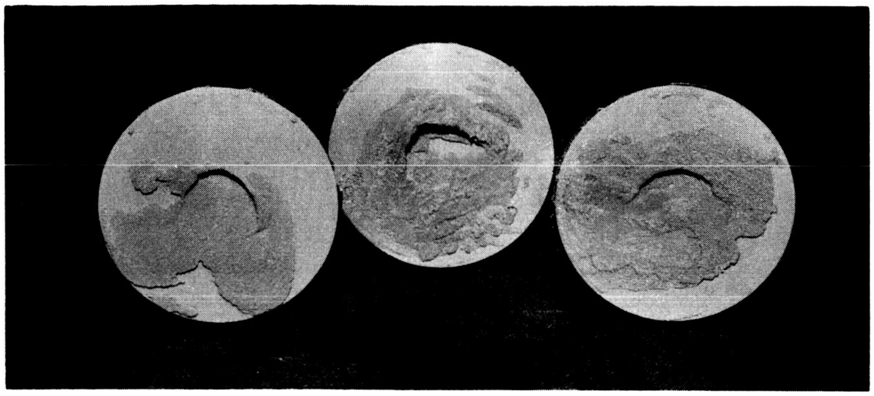


Figure 9. Shock Tensile Flange Failures

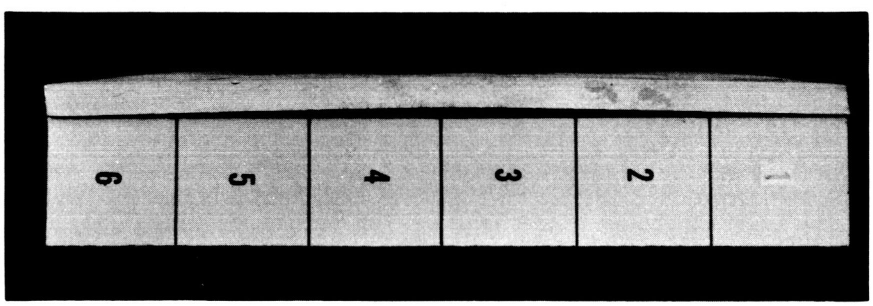


Figure 10. Base Plate Deformation, Shock Tensile Tests

Six additional studs were tested in static shear, using bare aluminum etched plate with the X-305 adhesive and both 1-mil and 5-mil Estane film. This was done for the purpose of comparing 1) the increase in strength due to the removal of entrapped air from the system, with 2) the use of bare plate rather than anodized plate. Results of these tests are shown in Table 16.

3. Shock Shear Tests

All shock shear tests were conducted using an Avco-type, SM 005-1 shock tester with a Tektronic oscilloscope (type 543) and a camera, coupled with an Endevco accelerometer (type 2215). This setup produced a shock pattern as shown in Figure 11.

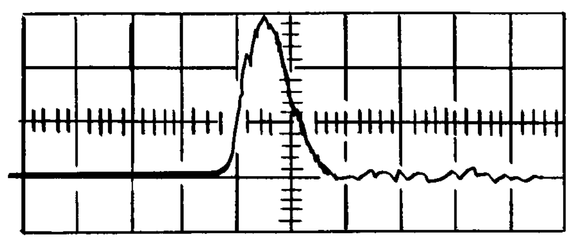


Figure 11. Typical Shock Pattern

This pattern describes a shock of approximately 100 g's and 4-milliseconds' duration, and is typical of all shock testing. The duration of the shock is reduced proportionately to the g level of the shock, as listed in the tables.

The shock fixture (Figure 12) was attached to the table of the Avco tester and the specimen to be tested was installed so that the baseplate was in a vertical position. A 10-lb weight was screwed onto the threaded portion of the stud. This weight had been devised so that it seated firmly against the 0.600-in. diameter shoulder of the stud, and its center of mass was 1.0 in. from the flat surface of the stud flange.

In Tables 17 through 20, which list test results on the four adhesive systems, the first two or three specimens were used to determine a failure level. For this reason, the latter tests on each system are more nearly representative of the load sustained by the system.

TABLE 16

STATIC SHEAR TESTS

Specimen No.	Adhesive	Flux Film	Load, lb	Type of Failure
1	X-305	0.001-in. Estane	1350	Cohesive
2	X-305		1500	
3	X-305		1350	
			Av. 1400	
1	X-305	0.005-in. Estane	1670	Stud broke at last thread
2	X-305		1700	Stud pulled out of flange
3	X-305		1700	Stud pulled out of flange
			Av. 1690	

NOTE: All tests were conducted using degassed X-305 resin and bare aluminum plates with a loading rate of 0.050-in./min.

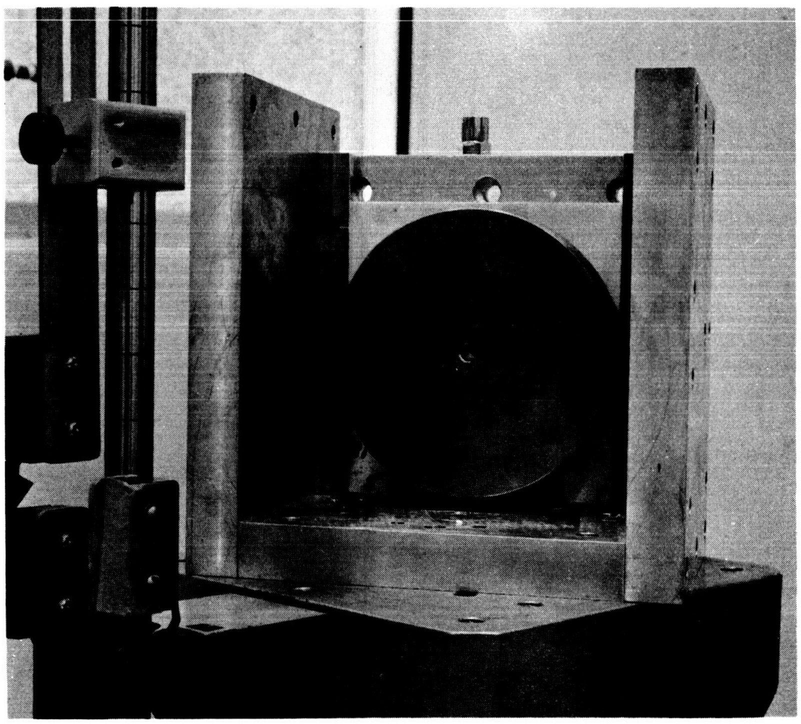


Figure 12. Avco Shock Tester with Shock Shear Fixture

TABLE 17

SHOCK SHEAR TESTS

X-305 Adhesive With 0.002-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Load In G's	No. of Shocks	Remarks
1	75	2			Adhesive failure
2	75	3			Adhesive failure
3	75	5	85	3	Stud failure, bolt area
4	75	1			Adhesive failure
5	75	1			
6	75	2			
7	75	5			Cohesive failure
8	75	4			Adhesive failure
9	75	1			
10	75	1			

TABLE 18

SHOCK SHEAR TESTS

7133/7130 Adhesive With 0.005-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Load In G's	No. of Shocks	Remarks
1					Used for gauge calibration
2	85	2			All failures cohesive
3	85	7			
4	85	2			
5	85	2			
6	85	2			
7	85	1			
8	85	2			
9	85	1			
10	85	1			

TABLE 19

SHOCK SHEAR TESTS

7133/3170 Adhesive With 0.002-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Load In G's	No. of Shocks	Remarks
1	85	1			All failures cohesive
2	75	1			
3	57	5	75	3	
4	64	3	75	2	
5	65	9	80	3	
6	75	5			
7	75	5			
8	75	5	85	1	
9	75	1			
10	75	5			

TABLE 20

SHOCK SHEAR TESTS

X-305 Adhesive With 0.005-in. Estane Flex Film

Specimen No.	Load In G's	No. of Shocks	Load In G's	No. of Shocks	Remarks
1	75	10	85	5	90 G-3 stud failure, flange area
2	90	3			Adhesive failure
3	90	6	100		Stud failure, flange area
4	100	1			Stud failure, bolt area
5	100	1			
6	100	2			
7	100	2			
8	100	5			
9	100	3			
10	100	1			Adhesive failure

Examination of these tables reveals that X-305 resin used with 0.005-in. Estane flex film is again the better adhesive system and could be considered more resistant to shock shear than the stud itself.

4. Vibration Testing

Specimens to be vibration tested were mounted in a holding fixture on the Ling Vibrator and a 10-lb weight screwed on the threaded portion of the stud. (This weight was devised so that it seated firmly against the 0.006-in. diameter shoulder of the stud and its center of mass was 1.0 in. from the flat surface of the stud flange.) Accelerometers were mounted on the fixture and on the weight so that the g-level input and resonant frequency output could be measured.

Studs were subjected to a resonant search from 7 cps to 2000 cps, and a Sanborn recorder was utilized to determine which resonance was most severe. The studs were then subjected to a 5-minute dwell at the frequency of most severe resonance during which time the g level was steadily increased to stud failure or to the capacity of the equipment.

One-half of the stud specimens of each system were vibrated so that the stresses were imposed in the tensile axis. The other half were subjected to shear stresses. Results of these tests are shown in Tables 21 and 22.

As had been expected, the X-305 adhesive with the 0.005-in. Estane film was the outstanding bonding system for vibration resistance. When tested in the tensile axis, all five studs failed in the stud; of four studs tested in the shear axis, three failed in the stud with only one adhesive failure.

It is interesting to note that of the 29 studs utilizing the other three bonding systems tested in vibration shear and tension, only four failures were in the stud. Table 23 has been compiled to compare the high and low values and average load sustained by each of the four bonding systems for each test.

In static tension, X-305 1-mil Estane is the outstanding system, developing approximately 80% of the tensile strength of the stud.

The other three systems developed approximately equal strength.

In shock tensile, X-305 5-mil is the best system, failing three out of five studs (see Figure 11).

TABLE 21

VIBRATION TEST

TENSILE AXIS

Specimen No.	Resonant Frequency	Max. Acceleration Level		Post Test Examination Failed, Ruptured, No Apparent Damage
		Input (g's)	Output (g's)	
X305 5-Mil Estane -1	205	100	180	Mounting stud pulled out (3 min)
-3	230	100	160	Mounting stud pulled out (4 min)
-5	225	100	180	Mounting stud pulled out (1 min)
-7	160	50	110	Mounting stud pulled out (2 min)
-9	160	60	150	Mounting stud pulled out (2 min)
X305 2-Mil Estane -1	210	70	160	Mounting stud pulled out (3 min)
-3	220	100	190	Bonding came loose (2 min)
-5	230	100	180	Bonding came loose (2 min)
-7	235	100	160	Bonding came loose (2 min)
-9	250	100	180	Mounting stud pulled out (3 min)
7133/3170 5-Mil Estane -1	220	50	110	Bonding came loose (2 min)
-3	220	70	120	Bonding came loose (2 min)
-5	220	70	140	Bonding came loose (3 min)
-7	220	50	120	Bonding came loose (1 min)
-9	220	60	130	Bonding came loose (1/2 min)
7133/3170 2-Mil Estane -1	200	70	120	Bonding came loose (2 min)
-3	240	70	110	Bonding came loose (2 min)
-5	220	100	140	Mounting stud broken (2 min)
-7	200	100	140	Bonding came loose (1/2 min)
-9	220	100	130	Bonding came loose (3 min)

TABLE 22

VIBRATION TEST

SHEAR AXIS

Specimen No.	Resonant Frequency	Max. Acceleration Level		Post Test Examination Failed, Ruptured, No Apparent Damage
		Input (g's)	Output (g's)	
X-305 5-Mil Estane -2	135-70	13	30	Resonant frequency decreased to 70 cps. Bonding gave way
-4	122-85	60	55	Mass mount stud came loose
-6	135-85	65	100	Mass mounting stud pulled out of plate
-8	120-85	65	65	Mass mounting stud pulled out of plate
X-305 2-Mil Estane -2	120-80	30	45	Bonding came loose
-4	120-80	45	70	Stud broke and bonding came loose
-6	135	25	45	No apparent damage after 5 min of vibration
-8	120-95	20	35	Bonding came loose
-10	120-85	25	20	Bonding came loose
7133/3170 5-Mil Estane -2	90-82	25	30	Bonding came loose (2 min)
-4	90	28	30	No apparent damage after 5 min of vibration
-6	90-70	30	30	Bonding came loose after 3 min of vibration
-8	90-45	25	20	Bonding came loose after 2 min of vibration
7133/3170 2-Mil Estane -2	85-65	15	20	Bonding came loose after 2 min of vibration
-4	85-50	25	15	No apparent damage after 5 min of vibration
-6	85-45	15	20	Bonding came loose after 1 min of vibration
-8	85-50	15	15	Bonding came loose after 2 min of vibration
-10	90-45	28	20	Bonding came loose after 3 min of vibration

TABLE 23

SYSTEMS COMPARISON

Adhesive	Results	Static Tension, lb	Shock Tensile, g's	Shock Shear, g's	Vibration Tensile, g's	Vibration Shear, g's
A-305	High	3020	305	100	100	65
0.005-in. Estane	Low	1650	260	90	50	13
	Av.	2443	284	98	82	51
X-305	High	5230	260	85	100	45
0.002-in. Estane	Low	3390	100	75	70	20
	Av.	4010	131	76	94	29
7133/3170	High	3000	216	85	70	30
0.005-in. Estane	Low	2270	200	85	50	25
	Av.	2588	206	85	60	27
7133/3170	High	2720	200	85	100	28
0.002-in. Estane	Low	2120	138	75	70	15
	Av.	2400	154	77	88	19

The X-305 5-mil system was also best in shock shear and vibration shear, failing eight out of ten studs tested in shock shear, and three out of four in vibration shear.

The loads sustained in vibration tensile were too similar to be placed on a comparative basis; however, all five studs bonded with X-305 5-mil failed the studs, whereas the other three systems failed a total of three studs in fifteen specimens tested.

In a rerun of the static shear tests, the X-305 5-mil system failed all three studs tested.

Table 24 has been compiled to show the total number of tests on each specimen compared to the total number of studs failed.

TABLE 24

STUD FAILURE COMPARISON

Adhesive	Total Tests	Studs Failed
X-205 5-mil	46	22
X-305 2-mil	42	4
7133/3170 5-mil	40	0
7133/3170 2-mil	40	1

D. RECOMMENDATIONS

1. Studs

The stud configuration was designed in conformance with a theoretical analysis (see Summary Report No. 1, dated 12 March 1963) so that the maximum tearing stresses which could be resisted by the plate would be equivalent to the ultimate tensile strength of the 3/8-in. diameter stud. If this analysis is correct, the studs would, in practice, fail by tearing from the plate and by tensile failure of the stud, with equal frequency. Of the 27 stud failures experienced during testing, 17 have been flange tearing failures and 10 have been tensile failures of the mounting volt. This increase in flange failures can be explained by the fact that it was necessary to remove the flange anodic coating. This was accomplished by machining, during which operation a small amount of metal ($\approx$0.005-in. thick) was also removed from the back surface of the flange, slightly reducing its resistance to tearing stresses. It is felt that the tests have confirmed that the design for 3/8-in. diameter studs is optimum. It is expected that all failures of 1/4-in. diameter studs will occur in the bolt area.

The frequency of stud failures indicates that with proper adhesive systems and bonding procedures, the flange area is sufficient to support, under end use conditions, a load equal to or greater than that which can be supported by the 3/8-in. diameter bolt. It is recommended that no changes be made in the stud design, and that studs, as used during Phase II, be delivered for use in Phase III.

2. Adhesive

Two adhesives were tested during Phase II: Narmco's X-305, and the NASA formulation 3170/7133. The load-carrying ability of the 3170/7133 adhesive is limited by its cohesive strength. In the bonded stud application, the 3170/7133 adhesive failed in every specimen tested, with only one exception. Ultimate strength values averaged considerably less than with the X-305 adhesive.

Obtaining optimum bonds with the X-305 system requires that careful attention be given to surface preparation and bonding procedure details. However, bonds attained with the X-305 system have 1-1/2 to 2 times more load-carrying ability than bonds with the 3170/7133 adhesive.

Narmco has been engaged in active adhesive research since the founding of the company, and is in fact the originator of aircraft metal-to-metal bonding. Relatively recent work by Narmco on contracts such as NAS 8-1565, AF 33(616) 3007, and AF 33(657) 8047 have required that a very large number of adhesive systems be investigated. In Narmco's experience, the outstanding room temperature curing adhesive is the X-305 system. For most anticipated end use conditions, this system develops more load-carrying ability than does the stud. It is recommended, therefore, that all Phase III bonding be accomplished using the X-305 system.

3. Flexible Film Thickness

The liner film of Estane was demonstrated to be the best of those investigated during Phase I of this program. Reasons for the superiority were excellent temperature variation resistance and superior adhesive system compatibility. It is not possible to select one optimum film thickness. When shock or vibration is a factor in end use conditions, the 0.005-in. thickness has been shown to be superior. However, under static tensile loading, the 0.001-in. thickness has demonstrated improved load-carrying ability. It is recommended that Phase III studs be fabricated with part of them using 0.005-in. thick Estane, with the remainder using 0.001-in. thick Estane film. The proportions of 0.005-in. to 0.001-in. films will be determined by the Project Officer, depending upon the anticipated end use of the adhesive bonded studs.

III. PHASE III

A. INTRODUCTION

The following summary report covers the work accomplished during Phase III of the subject contract (1 September 1963 through 31 October 1963) and presents Narmco Research & Development's recommendations for optimum bonding procedures.

Fifty studs of each of the 1/4-in. and 3/8 in. diameters (as shown in Drawing RE5326) have been fabricated and delivered to the Project Officer at Marshall Space Flight Center, Huntsville, along with sufficient X-305 adhesive and 0.005-in. Estane film for bonding. In addition, three studs were bonded at Narmco to base plates for an immediate demonstration. Since tests in static tension had yielded the lowest results during earlier testing with no stud failures, they were chosen as being the most demonstrative of the bonding progress which had been made. One specimen was tested at Narmco and failed the stud at a load of 5440 lb. One specimen was tested at NASA and failed the stud at a load of 5190 lb. Earlier test results in static tension yielded an average load of 2443 lb, with a high load attained of 3020 lb. It can now be stated with certainty that, if proper bonding procedures are carefully followed, the X-305-Estane bonding system will consistently produce bonds which are stronger than the 3/8-in. diameter stud, in all tests considered during this program.

B. BONDING PROCEDURES

It must be emphasized that although good bonding practices must always be followed if optimum bonds are to be obtained, certain areas are quite critical. The wearing of white gloves is required when handling any surfaces for bonding, and even then touching of these surfaces must be kept at a minimum. A thumbprint on the bonding surface of the stud flange can, and usually will, reduce the effective load-carrying ability of the adhesive bonded stud by 70%. Similarly, any grease, oil, or other contamination on the bonding surfaces will result in reduced strengths.

Proper degassing of the mixed resin is second in importance to cleanliness. During the mixing of resin and accelerator, considerable air is entrapped. When the adhesive resin is pressed into a film of 0.0015-in. thickness, the visible surface may consist of as much as 50% air bubbles, resulting in a much greater percentage of loss in load-carrying ability of the stud. Optimum bonds demand that the X-305 resin system be vacuum degassed immediately after mixing and care must be taken thereafter to insure that no additional air is trapped in the bondline.

1. Aluminum Cleaning Procedure

Optimum performance of adhesive bonds depends on a clean, dry, grease-free surface. The recommended procedure for cleaning aluminum skins and stud flanges is as follows:

a. Vapor degrease, alkaline clean, rinse, and check for water break.

b. Immerse in sodium dichromate sulfuric acid solution for 13 to 15 minutes at 145°F to 155°F. The solution is made as follows:

Sodium dichromate (Fed 0-S-595A)	28.5 g
Sulfuric acid (Fed 0-A-115 Class A Grade 2)	285.0 g
Water	To make 1 liter

c. Spray-rinse with cold water ($<$ 75°F).

d. Immerse in cold water and repeat spray rinse.

e. Check for water break and dry in vented oven below 150°F. Protect clean, etched parts from contamination, finger prints, etc. Handle only with clean white gloves.

2. Adhesive System Preparation

a. Thoroughly mix 100 parts of base resin with 14 parts of curing agent.

b. Vacuum degas immediately after mixing. (Application and release of vacuum several times will accelerate degassing operation.)

c. Apply 3 to 5 g of resin to center of cleaned and etched stud location area.

d. Remove Teflon films from Estane liner.

e. Place Estane liner over adhesive on stud location area. Use stud flange to press resin to 0.0015-in. to 0.003-in. thickness.

f. Apply 3 to 5 g of resin to center of stud flange.

g. Center stud flange on Estane film and apply pressure to flow resin to 0.0015-in. to 0.003-in. thickness.

h. Apply 2-lb weight to stud and allow to cure 72 hours at over 70°F. (Application of 200° heat for 1-1/2 hours will complete cure and will result in slight strength increases.)

C. CONCLUSIONS

The continual increase in bond strengths throughout the program gives ample indication that strict adherence to the developed bonding technique is of the utmost importance. It has been shown that if optimum bonds are attained, the load-carrying ability of the adhesive system will exceed the strength of the aluminum stud when tested under any of the conditions considered during this program. It is recommended, however, that studs not be loaded in excess of 75% of the values given for 7075T6 Bolts in Mil Handbook -5, "Strength of Metal Aircraft Elements" (Armed Forces Supply Support Center).

D. RECOMMENDATIONS FOR FUTURE WORK

During the program just completed, bonding techniques for a room temperature curing adhesive system have been evolved which result in load-carrying abilities greater than that of the metal stud itself. However, additional work should be done in the following areas:

1. Development of capability of adhesive bonded studs at cryogenic temperatures

2. Development of LOX-compatible bonding methods for load-carrying studs

3. Determination of load-carrying ability of adhesive bonded studs on curved and irregular surfaces

4. Determination of the temperature-imposed limits of load-carrying ability of adhesive bonded studs

APPENDIX A

A CIRCULAR PLATE OF CONSTANT TEARING STRESS UNDER CONCENTRATED LOAD AT THE CENTER

APPENDIX A

A CIRCULAR PLATE OF CONSTANT TEARING STRESS UNDER CONCENTRATED LOAD AT THE CENTER

I. INTRODUCTION

A brief review of literature shows that no solution exists for the problem of a circular plate of nonuniform thickness bonded to elastic foundation under concentrated load at the center. The differential equation of the problem may be easily obtained by modifying Equation (e), Theory of Plates and Shells by S. Timoshenko and S. Wainowsky-Krieger (2nd edition, McGraw-Hill Book Company, Inc., 1959, p. 299). However, it is tedious to solve the differential equation of fourth order with variable coefficients; therefore, an approximate solution is obtained by the following technique:

> The plate of nonuniform thickness is first divided into a number of rings. The tearing stress at the middle surface of each ring is calculated by assuming that the thickness of the plate is constant and equal to that at the middle surface of the ring. This means that the theory of a circular plate of constant thickness on elastic foundation is assumed to be applicable to each region of the plate of nonuniform thickness. By using this approximate method, the optimum variation of the thickness of the plate on the condition of constant tearing stress can be easily determined and a numerical example shows the procedure.

II. THE TEARING STRESSES OF A CIRCULAR PLATE BONDED TO ELASTIC FOUNDATION AND SUBJECTED TO A CONCENTRATED LOAD AT THE CENTER

The general solution for a circular plate of uniform thickness h loaded at the center with a load P is given in the previous reference, p. 263, with the following result:

$$Z = A_1 \left(1 - \frac{x^4}{2^2 \cdot 4^2} + \ldots\right) + A_2 \left(x^2 - \frac{x^6}{4^2 \cdot 6^2} + \ldots\right)$$

$$+ A_3 \left[\left(1 - \frac{x^4}{2^2 \cdot 4^2} + \ldots\right) \log x + \frac{3}{128} x^4 - \frac{25}{1,769,472} x^8 + \ldots\right]$$

$$+ A_4 \left[\left(x^2 - \frac{x^6}{4^2 \cdot 6^2} + \ldots\right) \log x + \frac{5}{3,456} x^6 - \frac{1,054 \times 10^4}{442,368} x^{10} + \ldots\right] \quad (1)$$

Notations and sign conventions are defined to be consistent with those used in the reference whenever they are applicable.

The boundary conditions for the free edge of the plate are

$$\left(\frac{d^2Z}{dX^2} + \frac{\nu}{X} \frac{dZ}{dX}\right)_{x=\frac{a}{\ell}} = 0$$

$$\left(\frac{d^3Z}{dX^3} + \frac{1}{X} \frac{d^2Z}{dX^2} - \frac{1}{X^2} \frac{dZ}{dX}\right)_{x=\frac{a}{\ell}} = 0 \quad \ldots\ldots\ldots (2)$$

The finite condition of the deflection at the center of the plate requires

$$A_3 = 0 \quad (3)$$

Based on the condition that the sum of the shearing forces distributed over the lateral surface of an infinitesimal circular cylinder cut out of the plate at its center must balance the concentrated load P, one obtains

$$A_4 = \frac{P}{8 \pi k \ell^3} \quad (4)$$

The substitution of Equation (3) in (1) and the resulting expression for Z in Equations (2) yields

$$\alpha_1 A_1 + \beta_1 A_2 + \gamma_1 A_4 = 0$$

$$\alpha_2 A_1 + \beta_2 A_2 + \gamma_2 A_4 = 0 \qquad \ldots\ldots\ldots\ldots (10)$$

where the constants α_i , β_i , and γ_i $(i = 1, 2)$ are given by

$$\alpha_1 = \frac{3 + \nu}{16} \left(\frac{a}{\ell}\right)^2$$

$$\beta_1 = \frac{5 + \nu}{96} \left(\frac{a}{\ell}\right)^4 - 2(1 + \nu) \qquad (6)$$

$$\gamma_1 = \left[\frac{5 + \nu}{96} \left(\frac{a}{\ell}\right)^4 - 2(1 + \nu)\right] \log \frac{a}{\ell} - (3 + \nu) + \frac{13 + 4\nu}{576} \left(\frac{a}{\ell}\right)^4$$

$$\alpha_2 = \frac{a}{2\ell}$$

$$\beta_2 = \frac{1}{4} \left(\frac{a}{\ell}\right)^3 \qquad (7)$$

$$\gamma_2 = \left(\frac{a}{\ell}\right)^3 \left(\frac{1}{4} \log \frac{a}{\ell} - \frac{1}{16}\right) - \frac{4\ell}{a} + \frac{527}{110,592 \times 25} \left(\frac{a}{\ell}\right)^7$$

It is noted that constants α_i , β_i , and γ_i are obtained by taking the first two terms in each series of the solution (1). Solving Equations (5) simultaneously yields

$$A_1 = \frac{\beta_1\gamma_2 - \beta_2\gamma_1}{\alpha_1\beta_2 - \alpha_2\beta_1} A_4$$

$$A_2 = \frac{\gamma_1\alpha_2 - \gamma_2\alpha_1}{\alpha_1\beta_2 - \alpha_2\beta_1} A_4 \qquad (8)$$

The tearing stresses is given by

$$\sigma_z = K \ell Z \qquad (9)$$

For a given set of material properties and plate dimensions the constants α_i , β_i , γ_i, and A_j can be found from Equations (4), (6), (7), and (8).

The values of Z are determined by Equation (1) and then the stresses σ_z by Equation (9).

III. AN APPROXIMATE METHOD ON THE DETERMINATION OF THE SHAPE OF THE CIRCULAR PLATE FOR UNIFORM TEARING STRESSES

A circular plate of arbitrary nonuniform thickness is divided into n rings as shown in Figure 13. The width of the m^{th} ring is taken to be that at $r = \frac{1}{2}(r_{m-1} + r_m)$ and is determined, in such a way that the tearing stress of the ring at $r = \frac{1}{2}(r_{m-1}+r_m)$ may be in an approximate manner obtained by calculating the stress of the plate at $r = \frac{1}{2}(r_{m-1} + r_m)$ with the thickness of the plate being the width of the ring.

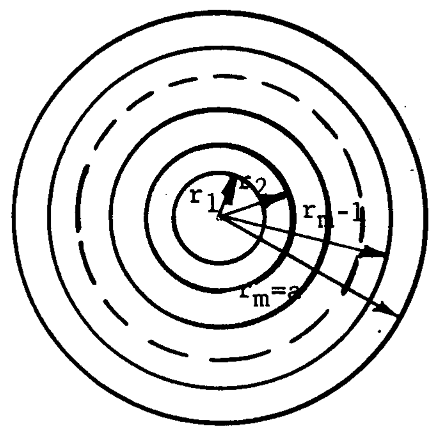


Figure 13. A Circular Plate of Nonuniform Thickness

If the prescribed tearing stress is denoted by σ_w, then one obtains from Equation (9):

$$\sigma_w = \delta\, h_M^{3/4}\, Z_M \tag{10}$$

where h_M and Z_M are the thickness and the value of Z at $r = \frac{1}{2}(r_{m-1} + r_m)$ and where

$$\delta = \left[\frac{EK^3}{12(1 - \nu^2)}\right]^{1/4} \tag{11}$$

It can be seen that the value of h_M satisfying Equation (10) is the required thickness of the m^{th} ring.

IV. NUMERICAL CALCULATION

In the following numerical example the material properties, the radius of the circular plate and the tearing stress are assumed to be given by

$E = 30 \times 10^6$ psi $\nu = 0.3$

$K = 12 \times 10^3$ lb/in.^{2}/in. $a = 1$ in.

$\sigma_w = 4{,}350$ psi $d = 0.25$ in.

Now the circular plate is divided into four regions as shown in Figure 14. The most inner region is the stud in the present case, which is not considered here.

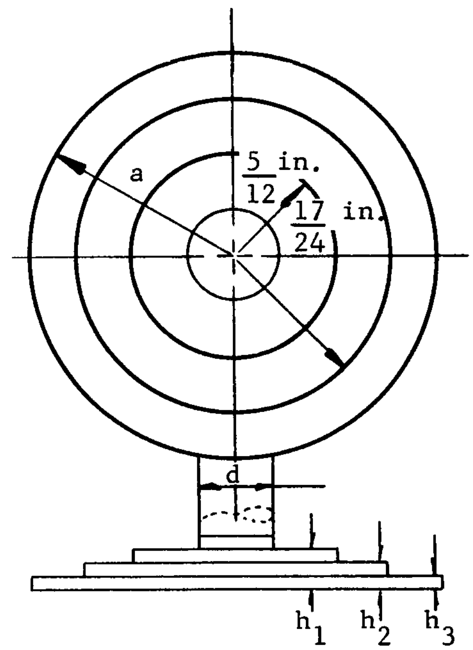


Figure 14. A Circular Plate With Variable Thickness

Start the calculation by assuming

$$h_2 = 0.08 \text{ in.}$$

Using Equations (4), (6), and (7) one obtains

$$A_4 = 0.2248$$

$$\alpha_1 = 0.6027; \quad \alpha_2 = 0.8547$$

$$\beta_1 = -2.129; \quad \beta_2 = 1.249$$

$$\gamma_1 = -4.231; \quad \gamma_2 = -1.977$$

The substitution of these values into Equations (8) yields

$$A_1 = 0.8300$$

$$A_2 = -0.2115$$

Substituting the values of A_1, A_2, $A_3(=0)$, and A_4 in Equation (1) and setting $X = 0.9615$ yields

$$Z_M = 0.6163 \quad \text{at } r = \frac{1}{2}\left(\frac{5}{12} + \frac{17}{24}\right) = 0.5625$$

From Equation (10), one obtains

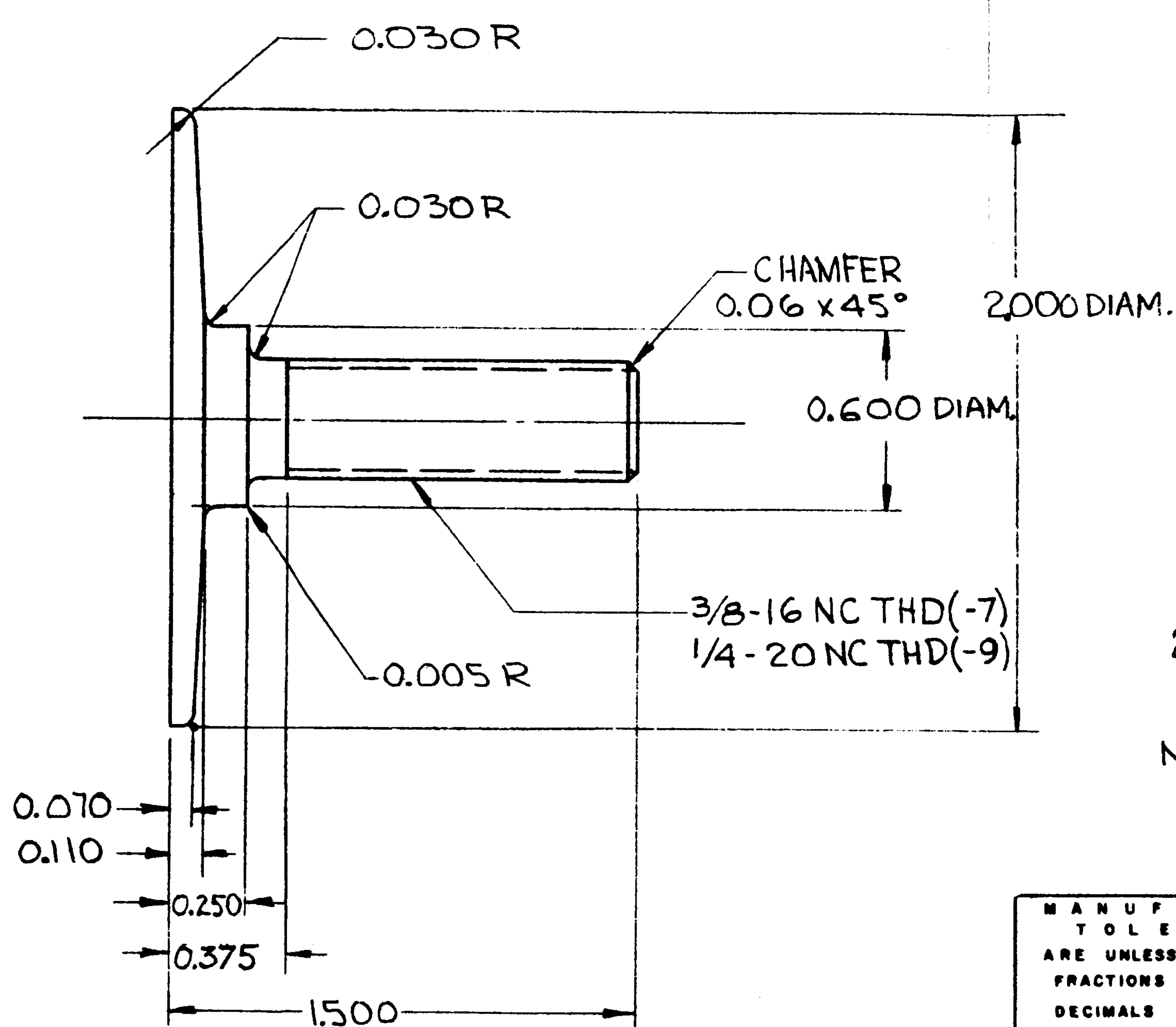
$$\sigma_w = 4322 \text{ psi}$$

Since the value of σ_w is close to the prescribed value, 4350 psi, the value of h_2 may be taken to be 0.08 in.

Similarly, the values of h_1 and h_3 are found to be 0.095 in. and 0.06 in. respectively.

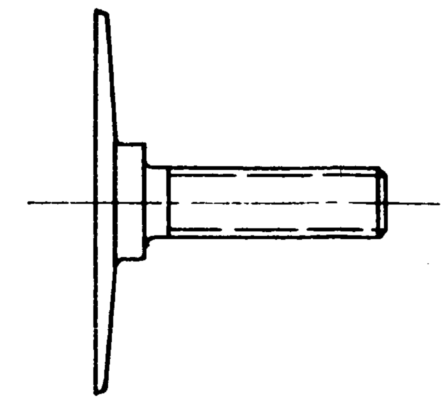
It can be verified that the maximum error of the tearing stresses calculated by using $h = 0.095$ in., 0.08 in., and 0.06 in., is less than 0.7% compared to the prescribed tearing stress.

Prepared by: C. Y. Chia
C. Y. Chia



SCALE 2/1

-7 SHOWN
-9 SAME EXCEPT FOR THREAD



FULL SCALE

-7 SHOWN

NOTES :

1. MATERIAL TO BE 7075-T6 ALUMINUM ALLOY
2. ANODIZE ALL PARTS AFTER MACHINING.

MANUFACTURING TOLERANCES ARE UNLESS OTHERWISE NOTED:
FRACTIONS ± .031
DECIMALS .XX ± .020
.XXX ± .005
ANGLES ± 1/2 DEG.
ALL MACHINED SURFACES & AS NOTED REF. NAS 30

DESIGN ROBINSON 1-3-63
STRESS C. Y. Chia
PROCESS
TOOLING
CHECK
WEIGHT
APPROVED [signature]

HEAT TREAT
FINISH
TITLE STUD

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NARMCO
RESEARCH & DEVELOPMENT
A DIVISION OF TELECOMPUTING CORPORATION
3540 AERO COURT
SAN DIEGO 23, CALIFORNIA

SCALE NOTED
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DWG. NO. RE 5326
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CHANGE LETTER